IMAGING A THREE-DIMENSIONAL STRUCTURE BY CONFOCAL FOCUSSING AN ARRAY OF LIGHT BEAMS

FIELD OF THE INVENTION

This invention in the field of imaging techniques and relates to a method and an apparatus for non-contact imaging of three-dimensional structures, particularly useful for direct surveying of teeth.

5 BACKGROUND OF THE INVENTION

A great variety of methods and systems have been developed for direct optical measurement of teeth and the subsequent automatic manufacture of dentures. The term *"direct optical measurement"* signifies surveying of teeth in the oral cavity of a patient. This facilitates the obtainment of digital
10 constructional data necessary for the computer-assisted design (CAD) or computer-assisted manufacture (CAM) of tooth replacements without having to make any cast impressions of the teeth. Such systems typically includes an optical probe coupled to an optical pick-up or receiver such as charge coupled device (CCD) and a processor implementing a suitable image processing
15 technique to design and fabricate virtually the desired product.

One conventional technique of the kind specified is based on a laser-triangulation method for measurement of the distance between the surface of the tooth and the optical distance probe, which is inserted into the

oral cavity of the patient. The main drawback of this technique consists of the following. It is assumed that the surface of the tooth reflects optimally, e.g. Lambert's reflection. Unfortunately, this is not the case in practice and often the data that is obtained is not accurate.

5   Other techniques, which are embodied in CEREC-1 and CEREC-2 systems commercially available from Siemens GmbH or Sirona Dental Systems, utilize the light-section method and phase-shift method, respectively. Both systems employ a specially designed hand-held probe to measure the three-dimensional coordinates of a prepared tooth. However, the methods

10   require a specific coating (i.e. measurement powder and white-pigments suspension, respectively) to be deposited to the tooth. The thickness of the coating layer should meet specific, difficult to control requirements, which leads to inaccuracies in the measurement data.

          By yet another technique, mapping of teeth surface is based on

15   physical scanning of the surface by a probe and by determining the probe's position, e.g. by optical or other remote sensing means, the surface may be imaged.

          U.S. Patent No. 5,372,502 discloses an optical probe for three-dimensional surveying. The operation of the probe is based on the

20   following. Various patterns are projected onto the tooth or teeth to be measured and corresponding plurality of distorted patterns are captured by the probe. Each interaction provides refinement of the topography.

SUMMARY OF THE INVENTION

          The present invention is directed to a method and apparatus for

25   imaging three-dimensional structures. A preferred, non-limiting embodiment, is concerned with the imaging of a three-dimensional topology of a teeth segment, particularly such where one or more teeth are missing. This may allow the generation of data for subsequent use in design and manufacture of,

for example, prosthesis of one or more teeth for incorporation into said teeth segment. Particular examples are the manufacture of crowns or bridges.

The present invention provides, by a first of its aspects, a method for determining surface topology of a portion of a three-dimensional structure,
5   comprising:

(a) providing an array of incident light beams propagating in an optical path leading through a focusing optics and a probing face; the focusing optics defining one or more focal planes forward said probing face in a position changeable by said optics, each light
10   beam having its focus on one of said one or more focal plane; the beams generating a plurality of illuminated spots on the structure;

(b) detecting intensity of returned light beams propagating from each of these spots along an optical path opposite to that of the incident light;

15   (c) repeating steps (a) and (b) a plurality of times, each time changing position of the focal plane relative to the structure; and

(d) for each of the illuminated spots, determining a spot-specific position, being the position of the respective focal plane, yielding a maximum measured intensity of a respective returned light beam;
20   and

(e) based on the determined spot-specific positions, generating data representative of the topology of said portion.

By a further of its aspects, the present invention provides an apparatus for determining surface topology of a portion of a
25   three-dimensional structure, comprising:

- a probing member with a sensing face;

- an illumination unit for providing an array of incident light beams transmitted towards the structure along an optical path through said probing unit to generate illuminated spots on said portion;

- a light focusing optics defining one or more focal planes forward said probing face at a position changeable by said optics, each light beam having its focus on one of said one or more focal plane ;

- a translation mechanism coupled to said focusing optics for displacing said

5   focal plane relative to the structure along an axis defined by the propagation of the incident light beams;

- a detector having an array of sensing elements for measuring intensity of each of a plurality of light beams returning from said spots propagating through an optical path opposite to that of the incident light beams;

10   - a processor coupled to said detector for determining for each light beam a spot-specific position, being the position of the respective focal plane of said one or more focal planes yielding maximum measured intensity of the returned light beam, and based on the determined spot-specific positions, generating data representative of the topology of said portion.

15   The probing member, the illumination unit and the focusing optics and the translation mechanism are preferably included together in one device, typically a hand-held device. The device preferably includes also the detector.

The determination of the spot-specific positions in fact amounts to determination of the in-focus distance. The determination of the spot-specific

20   position may be by measuring the intensity *per se*, or typically is performed by measuring the displacement (S) derivative of the intensity (I) curve (dI/dS) and determining the relative position in which this derivative function indicates a maximum maximum intensity. The term *"spot-specific position (SSP)"* will be used to denote the relative in-focus position regardless of the

25   manner in which it is determined. It should be understood that the SSP is always a relative position as the absolute position depends on the position of the sensing face. However the generation of the surface topology does not require knowledge of the absolute position, as all dimensions in the cubic field of view are absolute.

The SSP for each illuminated spot will be different for different spots. The position of each spot in an X-Y frame of reference is known and by knowing the relative positions of the focal plane needed in order to obtain maximum intensity (namely by determining the SSP) , the Z or depth coordinate can be associated with each spot and thus by knowing the X-Y-Z coordinates of each spot the surface topology can be generated.

In accordance with one embodiment, in order to determine the Z coordinate (namely the SSP) of each illuminated spot the position of the focal plane is scanned over the entire range of depth or Z component possible for the measured surface portion. In accordance with another embodiment the beams have components which each has a different focal plane. Thus, in accordance with this latter embodiment by independent determination of SSP for the different light components, e.g. 2 or 3 with respective corresponding 2 or 3 focal planes, the position of the focal planes may be changed by the focusing optics to scan only part of the possible depth range, with all focal planes together covering the expected depth range. In accordance with yet another embodiment, the determination of the SSP involves a focal plane scan of only part of the potential depth range and for illuminated spots where a maximum illuminated intensity was not reached, the SSP is determined by extrapolation from the measured values or other mathematical signal processing methods.

The method and apparatus of the invention are suitable for determining a surface topology of a wide variety of three-dimensional structures. A preferred implementation of method and apparatus of the invention are in determining surface topology of a teeth section.

In accordance with one embodiment of the invention, the method and apparatus are used to construct an object to be fitted within said structure. In accordance with the above preferred embodiment, such an object is at least one tooth or a portion of a tooth missing in the teeth section. Specific

examples include a crown to be fitted on a tooth stump or a bridge to be fitted within teeth.

By one embodiment of the invention, the plurality of incident light beams are produced by splitting a parent beam. Alternatively, each incident light beam or a group of incident light beams may be emitted by a different light emitter. In accordance with a preferred embodiment, light emitted from a light emitter passes through a diffraction or refraction optics to obtain the array of light beams.

In accordance with one embodiment, the parent light beam is light emitted from a single light emitter. In accordance with another embodiment, the parent light beam is composed of different light components, generated by different light emitters, the different light components differing from one another by at least one detectable parameter. Such a detectable parameter may, for example be wavelength, phase, different duration or pulse pattern, etc. Typically, each of said light components has its focus in a plane differently distanced from the structure than other light components. In such a case, when the focal plane of the optics is changed, simultaneously the different ranges of depth (or Z component) will be scanned. Thus, in such a case, for each illuminated spot there will be at least one light component which will yield a maximum intensity, and the focal distance associated with this light component will then define the Z component of the specific spot.

In accordance with an embodiment of the invention the incident light beams are polarized. In accordance with this embodiment, typically the apparatus comprises a polarization filter for filtering out, from the returned light beams, light components having the polarization of the incident light, whereby light which is detected is that which has an opposite polarization to that of the incident light.

The data representative of said topology may be used for virtual reconstruction of said surface topology, namely for reconstruction within the

computer environment. The reconstructed topology may be represented on a screen, may be printed, etc., as generally known *per se*. Furthermore, the data representative of said topology may also be used for visual or physical construction of an object to be fitted within said structure. In the case of the

5   preferred embodiment noted above, where said structure is a teeth section with at least one missing tooth or tooth portion, said object is a prosthesis of one or more tooth, e.g. a crown or a bridge.

By determining surface topologies of adjacent portions, at times from two or more different angular locations relative to the structure, and then

10   combining such surface topologies, e.g in a manner known *per se*, a complete three-dimensional representation of the entire structure may be obtained. Data representative of such a representation may, for example, be used for virtual or physical reconstruction of the structure, may be transmitted to another apparatus or system for such reconstruction, e.g. to a CAD/CAM apparatus.

15   Typically, but not exclusively, the apparatus of the invention comprises a communication port for connection to a communication network which may be a computer network, a telephone network, a wireless communication network, etc.

BRIEF DESCRIPTION OF THE DRAWINGS

20   In order to understand the invention and to see how it may be carried .out in practice, a preferred embodiment will now be described, by way of non-limiting example only, with reference to the accompanying drawings, in which:

Figs. 1A and 1B are a schematic illustration by way of a block diagram

25   of an apparatus in accordance with an embodiment of the invention (Fig. 1B is a continuation of Fig. 1A);

Fig. 2A is a top view of a probing member in accordance with an embodiment of the invention;

Fig. 2B is a longitudinal cross-section through line II-II in Fig. 2A, depicting also some exemplary rays passing therethrough;

Fig. 3 is a schematic illustration of another embodiment of a probing member ; and

5   Fig. 4 is a schematic illustration of an embodiment where the parent light beam, and thus each of the incident light beams, is composed of several light components, each originating from a different light emitter.

DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT

10   Reference is first being made to Figs. 1A and 1B illustrating, by way of a block diagram an apparatus generally designated 20, consisting of an optical device 22 coupled to a processor 24. The embodiment illustrated in Fig. 1 is particularly useful for determining the three-dimensional structure of a teeth segment 26, particularly a teeth segment where at least one tooth or

15   portion of tooth is missing for the purpose of generating data of such a segment for subsequent use in design or manufacture of a prosthesis of the missing at least one tooth or portion, e.g. a crown or a bridge. It should however be noted, that the invention is not limited to this embodiment, and applies, *mutatis mutandis*, also to a variety of other applications of imaging of

20   three-dimensional structure of objects, e.g. for the recordal or archeological objects, for imaging of a three-dimensional structure of any of a variety of biological tissues, etc.

Optical device 22 comprises, in this specific embodiment, a semiconductor laser unit 28 emitting a laser light, as represented by arrow 30.

25   The light passes through a polarizer 32 which gives rise to a certain polarization of the light passing through polarizer 32. The light then enters into an optic expander 34 which improves the numerical aperture of the light beam 30. The light beam 30 then passes through a module 38, which may, for example, be a grating or a micro lens array which splits the parent beam 30

into a plurality of incident light beams **36**, represented here, for ease of illustration, by a single line. The operation principles of module **38** are known *per se* and the art and these principles will thus not be elaborated herein.

The light unit **22** further comprises a partially transparent mirror **40**
5   having a small central aperture. It allows transfer of light from the laser source through the downstream optics, but reflects light travelling in the opposite direction. It should be noted that in principle, rather than a partially transparent mirror other optical components with a similar function may also be used, e.g. a beam splitter. The aperture in the mirror **40** improves the
10   measurement accuracy of the apparatus. As a result of this mirror structure the light beams will yield a light annulus on the illuminated area of the imaged object as long as the area is not in focus; and the annulus will turn into a completely illuminated spot once in focus. This will ensure that a difference between the measured intensity when out-of- and in-focus will be larger.
15   Another advantage of a mirror of this kind, as opposed to a beam splitter, is that in the case of the mirror internal reflections which occur in a beam splitter are avoided, and hence the signal-to-noise ratio improves.

The unit further comprises a confocal optics **42**, typically operating in a telecentric mode, a relay optics **44**, and an endoscopic probing member
20   **46**. Elements **42, 44** and **46** are generally as known *per se*. It should however be noted that telecentric confocal optics avoids distance-introduced magnification changes and maintains the same magnification of the image over a wide range of distances in the Z direction (the Z direction being the direction of beam propagation). The relay optics
25   enables to maintain a certain numerical aperture of the beam's propagation.

The endoscopic probing member typically comprises a rigid, light-transmitting medium, which may be a hollow object defining within it a light transmission path or an object made of a light transmitting material, e.g. a glass body or tube. At its end, the endoscopic probe typically

comprises a mirror of the kind ensuring a total internal reflection and which thus directs the incident light beams towards the teeth segment **26**. The endoscope **46** thus emits a plurality of incident light beams **48** impinging on to the surface of the teeth section.

5   Incident light beams **48** form an array of light beams arranged in an X-Y plane, in the Cartasian frame **50**, propagating along the Z axis. As the surface on which the incident light beams hits is an uneven surface, the illuminated spots **52** are displaced from one another along the Z axis, at different (X_i, Y_i) locations. Thus, while a spot at one location may be in
10   focus of the optical element **42**, spots at other locations may be out-of-focus. Therefore, the light intensity of the returned light beams (see below) of the focused spots will be at its peak, while the light intensity at other spots will be off peak. Thus, for each illuminated spot, a plurality of measurements of light intensity are made at different positions along the
15   Z-axis and for each of such (X_i, Y_i) location, typically the derivative of the intensity over distance (Z) will be made, the Z_i yielding maximum derivative, Z_0, will be the in-focus distance. As pointed out above, where, as a result of use of the punctured mirror **40**, the incident light forms a light disk on the surface when out of focus and a complete light spot only when
20   in focus, the distance derivative will be larger when approaching in-focus position thus increasing accuracy of the measurement.

        The light scattered from each of the light spots includes a beam travelling initially in the Z axis along the opposite direction of the optical path traveled by the incident light beams. Each returned light beam **54**
25   corresponds to one of the incident light beams **36**. Given the unsymmetrical properties of mirror **40**, the returned light beams are reflected in the direction of the detection optics generally designated **60**. The detection optics comprises a polarizer **62** that has a plane of preferred polarization oriented normal to the plane polarization of polarizer **32**. The returned

polarized light beam **54** pass through an imaging optic **64**, typically a lens or a plurality of lenses, and then through a matrix **66** comprising an array of pinholes. CCD camera has a matrix or sensing elements each representing a pixel of the image and each one corresponding to one pinhole in the array

5 **66**.

The CCD camera is connected to the image-capturing module **80** of processor unit **24**. Thus, each light intensity measured in each of the sensing elements of the CCD camera, is then grabbed and analyzed, in a manner to be described below, by processor **24**.

10 Unit **22** further comprises a control module **70** connected to a controlling operation of both semi-conducting laser **28** and a motor **72**. Motor **72** is linked to telecentric confocal optics **42** for changing the relative location of the focal plane of the optics **42** along the Z-axis. In a single sequence of operation, control unit **70** induces motor **72** to displace the

15 optical element **42** to change the focal plane location and then, after receipt of a feedback that the location has changed, control module **70** will induce laser **28** to generate a light pulse. At the same time it will synchronize image-capturing module **80** to grab data representative of the light intensity from each of the sensing elements. Then in subsequent sequences the focal

20 plane will change in the same manner and the data capturing will continue over a wide focal range of optics **44, 44**.

Image capturing module **80** is connected to a CPU **82** which then determines the relative intensity in each pixel over the entire range of focal planes of optics **42, 44**. As explained above, once a certain light spot is in

25 focus, the measured intensity will be maximal. Thus, by determining the Z_i corresponding to the maximal light intensity or by determining the maximum displacement derivative of the light intensity, for each pixel, , the relative position of each light spot along the Z axis can be determined. Thus, data representative of the three-dimensional pattern of a surface in the

teeth segment, can be obtained. This three-dimensional representation may be displayed on a display **84** and manipulated for viewing, e.g. viewing from different angles, zooming-in or out, by the user control module **86** (typically a computer keyboard). In addition, the data representative of the

5   surface topology may be transmitted through an appropriate data port, e.g. a modem **88**, through any communication network, e.g. telephone line **90**, to a recipient (not shown) e.g. to an off-site CAD/CAM apparatus (not shown).

By capturing, in this manner, an image from two or more angular

10   locations around the structure, e.g. in the case of a teeth segment from the buccal direction, from the lingal direction and optionally from above the teeth, an accurate three-dimensional representation of the teeth segment may be reconstructed. This may allow a virtual reconstruction of the three-dimensional structure in a computerized environment or a physical

15   reconstruction in a CAD/CAM apparatus.

As already pointed out above, a particular and preferred application is imaging of a segment of teeth having at least one missing tooth or a portion of a tooth, and the image can then be used for the design and subsequent manufacture of a crown or any other prosthesis to be fitted into

20   this segment.

Reference is now being made to Figs. 2A AND 2B illustrating a probing member **90** in accordance with one, currently preferred, embodiment of the invention. The probing member **90** is made of a light transmissive material, typically glass and is composed of an anterior

25   segment **91** and a posterior segment **92**, tightly glued together in an optically transmissive manner at **93**. Slanted face **94** is covered by a totally reflective mirror layer **95**. Glass disk **96** defining a sensing surface **97** is disposed at the bottom in a manner leaving an air gap **98**. The disk is fixed in position by a holding structure which is not shown. Three light rays are

99 are represented schematically. As can be seen, they bounce at the walls of the probing member at an angle in which the walls are totally reflective and finally bounce on mirror 94 and reflected from there out through the sensing face 97. The light rays focus on focusing plane 100, the position of
5 which can be changed by the focusing optics (not shown in this figure).

Reference is now being made to Fig. 3, which is a schematic illustration of an endoscopic probe in accordance with an embodiment of the invention. The endoscopic probe, generally designated 101, has a stem 102 defining a light transmission path (e.g., containing a void
10 elongated space, being made of or having an interior made of a light transmitting material. Probe 102 has a trough-like probe end 104 with two lateral probe members 106 and 108 and a top probe member 110. The optical fibers have light emitting ends in members 106, 108 and 110 whereby the light is emitted in a direction normal to the planes defined by
15 these members towards the interior of the trough-like structure 104. The probe is placed over a teeth segment 120, which in the illustrated case consists of two teeth 122 and 124, and a stamp 126 of a tooth for placement of a crown thereon. Such a probe will allow the simultaneous imaging of the surface topology of the teeth segment from three angles and
20 subsequently the generation of a three-dimensional structure of this segment.

Reference is now being made to Fig. 4. In this figure, a number of components of an apparatus generally designated 150 in accordance with another embodiment are shown. Other components, not shown, may be
25 similar to those of the embodiment shown in Fig. 1. In this apparatus a parent light beam 152 is a combination of light emitted by a number of laser light emitters 154A, 154B and 154C. Optic expander unit 156 then expands the single parent beam into an array of incident light beams 158. Incident

light beams pass through unidirectional mirror **160**, then through optic unit **162** towards object **164**.

The different light components composing parent beam **152** may for example be different wavelengths, a different one transmitted from each of

5   laser emitters **154A-C**. Thus, parent light beam **152** and each of incident light beams **158** will be composed of three different light components. The image of the optics, or an optical arrangement associated with each of light emitters may be arranged such that each light component focuses on a different plane, P_A, P_B and P_C, respectively. Thus in the position shown in

10   Fig. 3, incident light beam **158A** bounces on the surface at spot **170A** which in the specific optical arrangement of optics **162** is in the focal point for light component A (emitted by light emitter **154A**). Thus, the returned light beam **172A**, passing through detection optics **174** yield maximum measured intensity of light component A measured by two-dimensional array of

15   spectrophotometers **176, e.g. a 3 CHIP CCD camera**. Similarly, different maximal intensity will be reached for spots **170B** and **170C** for light components **B** and **C**, respectively.

Thus, by using different light components each one focused simultaneously at a different plane, the time measurement can be reduced as

20   different focal plane ranges can simultaneously be measured.